Perceptual Sensitivity to Infrasound is Not Associated With Wind Turbine Related Symptoms

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Objectives: Some individuals who live near wind farms have reported symptoms which they attribute to wind turbine infrasound (WTIS). The primary aim of this study was to investigate whether these individuals are perceptually sensitive to WTIS and thus possibly susceptible to WTIS-induced symptoms. A secondary aim was to investigate whether sham WTIS elicits stress, thus providing support for a nocebo explanation of symptom attributions.

Methods: A series of laboratory experiments was conducted with participants who attributed experienced symptoms to wind turbines (symptomatic group, n = 11) and controls who did not (asymptomatic group, n = 13). Discrimination ability (*d')* for wind turbine noise with and without infrasound (≤ 20 Hz) and low-frequency sound (≤ 100 Hz) was estimated with a two-interval same–different forced-choice task. Participants were also blindly exposed to WTIS for 7.5 minutes. Finally, participants underwent a sham infrasound exposure experiment without acoustic stimuli. Participants' perceived stress level and electrodermal activity were measured to evaluate participants' reactivity to WTIS and sham infrasound.

Results: Participants were not found to discriminate wind turbine noise with infrasound from wind turbine noise without infrasound or to react to WTIS exposure. Participants could discriminate wind turbine noise with low-frequency sound from wind turbine noise without low-frequency sound. No differences were observed between groups. Sham infrasound did not elicit stress in either group. The symptomatic group generally reported greater levels of perceived stress and more pre-existing symptoms than the asymptomatic group.

Conclusions: The results do not suggest an association between symptoms attributed to wind turbines and perceptual sensitivity to WTIS. Sham infrasound did not increase stress, and so symptomatic individuals may not associate symptoms with WTIS strongly enough for a nocebo response to occur. The greater reports of stress and pre-existing symptoms in the symptomatic group imply that symptoms might be misattributed to WTIS. Disturbance caused by audible low-frequency wind turbine noise might also influence symptom attributions.

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Tiivistelmä – Referat – Abstract

Tavoitteet: Osa tuulivoimaloiden lähellä asuvista selittää oireitaan tuulivoimaloiden tuottamalla infraäänellä. Tämän tutkimuksen ensisijainen tavoite oli selvittää, ovatko nämä yksilöt herkkiä havaitsemaan tuulivoimalainfraääntä ja siten mahdollisesti alttiita infraäänen aiheuttamille oireille. Tutkimuksen toissijainen tavoite oli selvittää, aiheuttaako lumeinfraäänialtistus stressiä, mikä tukisi oireiden syyksi ehdotettua nosebovaikutusta.

Menetelmät: Tutkimuksessa toteutettiin sarja laboratoriokokeita. Oireilevan ryhmän koehenkilöt (n = 11) selittivät oireitaan tuulivoimaloilla, kun taas oireettoman kontrolliryhmän koehenkilöt (n = 13) eivät. Kahden intervallin sama–eri pakkovalintatehtävää käytettiin arvioimaan, pystytäänkö todenmukainen tuulivoimalamelu erottamaan (*d'*) tuulivoimalamelusta, josta on poistettu infraääni (≤ 20 Hz) tai matalataajuinen ääni (≤ 100 Hz). Koehenkilöt myös sokkoaltistettiin tuulivoimalainfraäänelle 7.5 minuutin ajan. Lopuksi koehenkilöille esitettiin lumeinfraääntä kokeessa, joka ei sisältänyt ääniärsykkeitä. Koehenkilöiden reagoivuutta tuulivoimalainfraääneen ja lumeinfraääneen arvioitiin mittaamalla koehenkilöiden koettu stressitaso ja ihon sähkönjohtavuus.

Tulokset: Koehenkilöiden ei havaittu erottavan toisistaan todenmukaista tuulivoimalamelua ja tuulivoimalamelua ilman infraääntä. Koehenkilöiden ei myöskään havaittu reagoivan tuulivoimalainfraääneen sokkoaltistuskokeessa. Koehenkilöt kykenivät erottamaan toisistaan todenmukaisen tuulivoimalamelun ja tuulivoimalamelun ilman matalataajuista ääntä. Ryhmien välisiä eroja ei löydetty. Lumeinfraäänialtistus ei aiheuttanut stressiä kummassakaan ryhmässä. Oireilevien ryhmä raportoi yleisesti suurempaa koettua stressiä sekä enemmän ennestään koettuja oireita kuin oireettomien ryhmä.

Johtopäätökset: Tutkimustulokset eivät viittaa siihen, että tuulivoimaloilla selitettyjä oireita kokevat olisivat herkkiä havaitsemaan tuulivoimaloiden infraääntä. Oireilevat eivät välttämättä myöskään yhdistä oireitaan tuulivoimaloiden infraääneen niin vahvasti, että lumeinfraääni aiheuttaisi heissä nosebovasteen. Oireilevan ryhmän raportoima korkeampi stressitaso ja suurempi ennestään koettujen oireiden määrä viittaavat siihen, että oireiden syyn väärintulkinta saattaa selittää oireiden liittämistä tuulivoimaloihin. Kuultavissa olevasta matalataajuisesta tuulivoimalamelusta häiriintyminen saattaa myös vaikuttaa oireille annettuihin selityksiin.

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tuulivoimalamelu, infraääni, oire, terveys, nosebo, virheattribuutio

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Tämä tutkielma perustuu monitieteiseen tutkimusprojektiin, jonka tarkoituksena oli selvittää, onko tuulivoimaloiden tuottamalla infraäänellä kielteisiä terveysvaikutuksia. Projektista on julkaistu raportti: *Infrasound Does Not Explain Symptoms Related to Wind Turbines* (Maijala et al., 2020)

Acknowledgments

This thesis is based on a multidisciplinary research project to investigate whether wind turbine infrasound negatively impacts human health, published as a technical report titled *Infrasound Does Not Explain Symptoms Related to Wind Turbines* (Maijala et al., 2020). The project was commissioned by Finland's Prime Minister's Office (VN TEAS), in accordance with the Finnish National Energy and Climate Strategy for the year 2030. The project included a wind turbine noise measurement campaign, an epidemiological survey study, and provocation experiments. I was involved in the project's provocation experiments by participating in the pilot study and data analyses concerning participant characteristics, perceived stress, and electrodermal activity. Three participants from the project's provocation experiments have been excluded from the study population of this thesis so that all participants had a similar history of exposure to wind turbine noise. All statistical analyses have been performed independently from those in the technical report, except for perceived stress results in section 4.13.3 of the technical report, which I contributed to. A manuscript on the provocation experiments, *Annoyance, perception, and physiological effects of wind turbine infrasound* (Maijala et al.), has also been submitted for publication.

I thank project members at VTT, FIOH, and the University of Helsinki for readily involving me in this globally important project. I am grateful for being able to immerse myself in the complex and intriguing topic of wind turbine infrasound and related symptom experiences. Special thanks to my supervisor, Ilmari Kurki, who has been supportive, always available for guidance when I have needed it, and has steered me in the right direction with my research questions and writing. I also thank Kaisa Tiippana for her insightful and helpful comments on my thesis and Jari Lipsanen for his guidance on performing linear mixed-effects model analyses. Finally, a heartfelt thank you to my friends and loved ones who have given me constructive feedback and invaluable encouragement in completing this thesis.

Contents

1 Introduction

The health effects of infrasound generated by wind turbines are a subject of controversy. Whether exposure to wind turbine infrasound could influence health has been debated especially within non-peer-reviewed literature written by researchers (e.g., Chapman & Crichton, 2017; May & McMurtry, 2015; Punch & James, 2016) and in news and social media. In several western countries, a minority of residents living near wind farms have attributed various symptoms to wind turbine infrasound and low-frequency noise, including headache, fatigue, irregular heartbeat, sleep disturbance, increased blood pressure, dizziness, tinnitus, ear pressure, and nausea (review: Chapman & St. George, 2013; review: Farboud, Crunkhorn, & Trinidade, 2013; Maijala et al., 2020; McMurtry, 2011; Turunen, Tiittanen, Yli-Tuomi, Taimisto, & Lanki, 2020). The perceived harmfulness of wind turbine infrasound has caused significant distress in these residents, as is evident from public discussion. The fear of infrasound has been found to be the strongest factor in explaining the non-acceptance of wind power in Germany (Langer, Decker, Roosen, & Menrad, 2018).

Despite existing concerns, reviews and expert reports have generally concluded that evidence demonstrating direct effects of wind turbine infrasound (WTIS) on health is lacking, with many also concluding that harmful effects are unlikely (review: Turunen, 2017e). One reason why is that WTIS is probably inaudible in most situations. It has been proposed that symptoms have been misassociated with WTIS through cognitive processes such as the nocebo response and symptom misattribution (Chapman, St. George, Waller, & Cakic, 2013; Rubin, Burns, & Wessely, 2014). Results from experimental studies suggest that the nocebo response could explain why some individuals associate symptoms with wind turbines (Crichton, Dodd, Schmid, Gamble, Cundy, et al., 2014; Crichton, Dodd, Schmid, Gamble, & Petrie, 2014; Crichton, Dodd, Schmid, & Petrie, 2015; Crichton & Petrie, 2015).

However, the effects of long-term exposure to wind turbine infrasound have not been adequately examined to exclude the possibility of symptom induction (review: Freiberg, Schefter, Girbig, Murta, & Seidler, 2019; review: Lanki et al., 2017a; Seltenrich, 2019). Studies investigating responses to wind farm noise have also insufficiently included participants who could be especially sensitive to WTIS exposure (review: Alamir, Hansen, Zajamsek, & Catcheside, 2019; review: Carlile, Davy, Hillman, & Burgemeister, 2018) and thus develop symptoms. As the use of wind power is likely to increase along with increasing renewable energy demands (European Commission, 2019; Ministry of Economic Affairs and Employment of Finland, 2013), further studies on the effects of WTIS exposure are needed to rule out adverse influences on health and to explain symptoms attributed to wind turbine infrasound.

The current study is part of a comprehensive project to investigate whether wind turbine infrasound negatively impacts human health, following the Finnish National Energy and Climate Strategy for the year 2030 (Maijala et al., 2020). The purpose of this study is to examine whether individuals who attribute their symptoms to WTIS can detect or autonomically react to WTIS exposure and may thus be susceptible to developing symptoms. This study also investigated whether an alternative nocebo response explanation of symptom reports gains support. An experimental laboratory study utilizing realistic wind turbine noise was conducted, where participants who related their symptoms to wind turbines were compared with participants who did not.

1.2 Hearing Sound

Sound is a physical phenomenon where the vibration of matter causes the displacement of nearby particles in air or fluid, in turn causing particle density to oscillate between compression and rarefaction. This creates propagating sound pressure waves, which can be sensed by the auditory system. Fluctuations in pressure cause the eardrum of the middle ear to vibrate, leading to the movement of small bones that transmit these vibrations to the cochlea of the inner ear (McDermott, 2018). Within the cochlea, inner hair cells transduce sound into action potentials, which travel to the brain via the auditory nerve. The processing of sound in the brain leads to the perception of audible sound.

An ideal pure sound or tone is sinusoidal acoustic oscillation (Moore, 2013). Its frequency is its rate of oscillations, or the number of cycles per second, and is expressed in Hertz (Hz). Its amplitude corresponds to the extent of particle displacement or pressure fluctuation, which is related to the sound's sound pressure level. Sound pressure level is denoted in decibels (dB), a logarithmic unit describing the ratio of a given sound pressure to a reference sound pressure.

The human ear is not equally sensitive to all frequencies of sound, as is reflected by auditory thresholds and equal loudness contours for pure tones (review: Suzuki & Takeshima, 2004). The auditory threshold is typically considered the level of sound at which the average person can detect the sound 50 % of the time. In turn, equal loudness contours describe how tones with different frequencies require differing sound pressure levels to be perceived as equally loud. Sensitivity is highest for frequencies ranging from approximately 250 Hz to 12 000 Hz. The greater a sound's deviation from this frequency range, the higher its sound pressure level needs to be for it to be audible. To correspond with the sensitivity of human hearing, noise level is often reported as A-weighted sound pressure level (dBA), which attenuates low and high frequencies of sound.

Based on general agreement, sound with frequencies below 20 Hz is called *infrasound.* Sound below 200 Hz is considered low-frequency sound. Infrasound requires far greater sound pressure levels to be detected than midrange frequencies the ear is sensitive to, which is why infrasound is often considered inaudible. As reviewed by Moller and Pedersen (2004), auditory thresholds for infrasound tones are approximately 79 dB for 20 Hz, 95 dB for 10 Hz, and 110 dB for 5 Hz, with a standard deviation of 5 dB between individuals. Similar thresholds were obtained in a more recent experimental study by Kuehler, Fedtke, and Hensel (2015).

Pitch perception is lost for infrasound tones (review: Moller & Pedersen, 2004). At high enough sound pressure levels, infrasound can be perceived as pressure in the ears and sometimes as vibrations in other parts of the body. Although tactile perception of infrasound can occur, the perception of infrasound is believed to be primarily auditory, as the auditory threshold for infrasound is lower than the vibrotactile threshold of hearing and deaf individuals (Landström, Lundström, & Byström, 1983).

Studies have compared measured WTIS levels with auditory thresholds for pure infrasound tones to predict whether WTIS is audible (e.g., review: van Kamp & van den Berg, 2018). However, WTIS is a complex sound, comprised of multiple frequencies and variations in amplitude. How a complex sound is perceived cannot be directly inferred based on the perceptual qualities of its sinusoidal components (Moore, 2013). For example, the ear's response to two pure tones depends upon their intensities and their frequency difference. As a result, the presence of multiple tones can either amplify or diminish the response of the ear to a specific frequency. Likewise, the subjective perception of a tone’s pitch and loudness correlate respectively with the tone’s frequency and amplitude, but pitch and loudness perception of a complex sound is complexly influenced by the combination of frequencies a sound contains and their intensities. When predictions on the audibility of WTIS are based on pure infrasound tones, predictions may not be accurate due to differences in perceiving pure tones compared with complex sound.

1.3 Wind Turbine Noise

Wind turbine noise sounds like “a mechanical noise (such as a car running or a train in continuous motion) combined with an aerodynamic swishing sound (described as like a stick being swung through the air quickly)” (Tonin, 2018, p. 74). Wind turbine noise is mainly caused by aerodynamic phenomena that result from the movement of wind turbine blades (review: Carlile et al., 2018; review: Tonin, 2018).

Wind turbine noise contains a broad range of frequencies, including infra- and low-frequency sound (Maijala, Taimisto, & Yli-Tuomi, 2017; Tachibana, Yano, Fukushima, & Sueoka, 2014; Zajamšek, Hansen, Doolan, & Hansen, 2016). Infra- and low-frequency sound can propagate inside buildings and much farther from its source than higher frequency sound (review: Carlile et al., 2018). WTIS has been measured as far as 90 kilometers away from a wind farm (Marcillo, Arrowsmith, Blom, & Jones, 2015). Consequently, wind turbine infrasound and low-frequency noise may occur inside residences far away from wind farms.

Wind turbine noise can contain infrasound tones under 1 Hz, corresponding to the rate at which wind turbine blades rotate and its upper harmonics (review: Tonin, 2018; Zajamšek et al., 2016). The presence of wind turbine noise in sound measurements is often inferred based on tonal peaks in sound pressure level that occur in the infrasound range around 1–10 Hz (Marcillo et al., 2015; review: van Kamp & van den Berg, 2018; Zajamšek et al., 2016). Tonin (2018) has argued that the periodicity of WTIS makes it different from other environmental infrasound, which is random noise. Infrasound occurs in the environment due to various natural and man-made sources, including ocean waves, wind, air conditioning, and cars (Turnbull, Turner, & Walsh, 2012).

The highest sound pressure levels in wind turbine noise occur in the infra- and low-frequency range. In Finland, average sound pressure levels for narrowband infrasound have been measured to be approximately 60 dB and total average wind turbine noise to be approximately 70 dB when measured 200 meters away from the nearest wind turbine (Maijala et al., 2017). Similar average levels of background infrasound were measured in a city. When wind turbine noise was measured 2–3 kilometers away from the nearest wind turbine, the sound pressure level of infrasound decreased to approximately 55 dB and total average wind turbine noise to approximately 65 dB.

Higher WTIS levels can occur. In a large-scale wind turbine noise measurement campaign in Japan, WTIS under 2 Hz was found to reach 80 dB and WTIS around 8–16 Hz approximately 65 dB when noise was measured 136–561 meters away from the nearest wind turbine (Tachibana et al., 2014). Nonetheless, these levels are still below the auditory thresholds for infrasound tones. In the reviews of Turunen (2017a) and van Kamp and van den Berg (2018), it is similarly concluded that the sound pressure level of WTIS is typically below auditory thresholds. If pure tone thresholds are predictive of WTIS detectability, WTIS is unlikely to be perceptible in residential areas, even to sensitive individuals.

1.4 Proposed Physiological Effects of Wind Turbine Infrasound

1.4.1 Auditory Effects

Although it is generally agreed that there is no evidence demonstrating that WTIS affects health (review: Turunen, 2017e), various mechanisms have been proposed to explain how WTIS exposure could induce symptoms. In peer-reviewed literature, it is often considered whether WTIS could be audible and therefore related to symptom reports (review: Carlile et al., 2018; review: Tonin, 2018; Weichenberger et al., 2017). Auditory processing of infrasound could influence attention or affect, and thus theoretically lead to symptom development.

Long-term noise exposure may result in chronic stress and, in turn, an increased risk of cardiovascular and metabolic disease (review: Eriksson, Pershagen, & Nilsson, 2018; review: Münzel et al., 2018). Extreme or prolonged stress could also lead to a variety of somatic symptoms, including nausea, chest pain, abdominal pain, and fatigue, and exacerbate conditions such as asthma and eczema (review: Kozlowska, 2013). Another possible result of noise exposure is noise annoyance, which the World Health Organization currently considers an adverse health effect (WHO Regional Office for Europe, 2018). Once low-frequency noise exceeds the hearing threshold, noise annoyance increases rapidly as sound pressure level increases (review: Alamir et al., 2019). Coupled with the fact that auditory thresholds differ between individuals, it has been suggested that someone may be significantly disturbed by infrasound or low-frequency noise while others cannot even perceive it (Moller & Pedersen, 2004).

A prerequisite for any auditorily mediated health effects of WTIS is that infrasound must first stimulate the auditory organs of the inner ear. This requirement would be met if the auditory detection of WTIS was demonstrated. When considering measured WTIS levels along with auditory thresholds for infrasound tones, as reviewed in the previous sections, WTIS seems unlikely to be audible in residential areas. However, relying on auditory thresholds for infrasound tones is insufficient for assessing whether WTIS can be heard, as the perception of complex sounds cannot be simply predicted from the perceptual qualities of pure tones. Therefore, it would be beneficial to use realistic WTIS stimuli to investigate how the auditory system responds to WTIS. A study by Yokoyama, Sakamoto, and Tachibana (2014) seems to currently be the only peer-reviewed study to have done this.

Yokoyama et al. (2014) investigated the audibility of realistic WTIS in two laboratory experiments and concluded that WTIS is hardly audible. In their audibility experiment, a third of participants (3/10) were able to detect 20 Hz low-pass filtered wind turbine noise when infrasound components were approximately 70–80 dB. This sound is likely representative of WTIS at worst-case sound pressure levels which occur close to wind turbines (Tachibana et al., 2014). No participant could detect WTIS from wind turbine noise recorded over 300 meters from a wind turbine. Similar results were obtained in an auditory threshold experiment. Still, the finding that some participants could detect WTIS at high sound pressure levels may be explained by practical limitations in the filtering of sound stimuli, as a result of which theoretically audible frequencies above 20 Hz are attenuated but not completely removed. As none of the participants detected WTIS when a low-pass cutoff of 16 Hz was used, the study of Yokoyama et al. (2014) provides further support that WTIS is unlikely to be perceived in residential areas.

Weichenberger et al. (2017) conducted an fMRI study and have suggested that WTIS might be subliminally processed (i.e., that WTIS might stimulate the auditory system without being consciously perceived). When participants were presented with a 12 Hz tone slightly below their individual auditory threshold, local connectivity was found to increase in several brain areas compared to a no-tone condition. The functional connectivity of resting-state networks was also found to be influenced by the sub-threshold tone. However, audible infrasound, which was clearly perceived by all participants, was not found to influence activation anywhere in the brain. This odd combination of findings requires replication before the subliminal processing of WTIS can be further considered.

Carlile et al. (2018) have speculated in a review article whether WTIS could stimulate outer hair cells in the cochlea. This proposition is based primarily on the work of Salt and Hullar (2010). Several studies have shown that outer hair cells respond to low-frequency sound at lower sound pressure levels than inner hair cells which transduce sound. As a result, WTIS could hypothetically stimulate the auditory system even though sound pressure levels near wind farms are not high enough for WTIS to be audible. However, what is known about the function of outer hair cells is that they indirectly amplify the response of inner hair cells to low-amplitude sounds (McDermott, 2018), and this effect would be reflected in auditory thresholds. Current studies do not convincingly indicate that inaudible WTIS influences the auditory system as to cause symptoms.

1.4.2 Non-Auditory Effects

Proposed non-auditory effects of WTIS exposure include Vibroacoustic disease and Wind Turbine Syndrome. Vibroacoustic disease is described as extra-cellular thickening in organs due to excessive or repeated infra- or low-frequency sound exposure, and to be indicated by symptoms such as heart palpitations, migraines, balance disorders, epilepsy, fatigue, and a decrease in cognitive skills (review: Alves-Pereira & Castelo Branco, 2007a; Alves-Pereira & Castelo Branco, 2007b). Wind Turbine Syndrome is a symptom cluster suggested to be caused by disturbances to the vestibular system by low-frequency sound (Pierpont, 2009). This symptom cluster is said to include symptoms such as sleep disturbance, tinnitus, headache, nausea, and irritability.

Vibroacoustic disease and Wind Turbine Syndrome are sometimes referred to as proof of the harmfulness of WTIS in social media discussions and on wind power critical websites (such as stopthesethings.com). However, the evidential bases of both Wind Turbine Syndrome and Vibroacoustic disease have been heavily criticized for lack of scientific rigor, including reliance on case studies, questionable participant selection, and failing to account for the effects of pre-existing conditions on symptom reports (Chapman & George, 2013; Turunen, 2017c, 2017f; van Kamp & van den Berg, 2018). Wind Turbine Syndrome and Vibroacoustic disease are generally not considered plausible explanations for symptoms attributed to WTIS in peer-reviewed academic literature.

Endolymphatic hydrops has been tentatively discussed as a possible result of long-term exposure to infra- and low-frequency wind turbine noise (Salt & Hullar, 2010;

Ylikoski, 2017). In this condition, increased fluid in the inner ear causes symptoms such as tinnitus and dizziness, as well as a lower threshold for perceiving low-frequency sound. This suggestion is based on educated guesses, not direct evidence that infrasound levels in wind turbine noise can cause endolymphatic hydrops. It has also been speculated whether WTIS could cause sound-induced dizziness, called the Tullio phenomenon, in individuals with inner ear abnormalities (Salt & Hullar, 2010), or nausea in individuals susceptible to motion sickness (Schomer, Erdreich, Pamidighantam, & Boyle, 2015). However, it is acknowledged that the sensitivity of these potentially susceptible individuals to WTIS levels is not known.

1.5 Previous Studies on Wind Turbine Sound and Health

A recent extensive review by Freiberg et al. (2019) outlines most of the available research conducted on the health effects of wind turbines, covering publications from 2000 to 2017. A literature diverse in its methods and examined associations has accumulated, with most studies published after 2010. However, studies specifically investigating whether WTIS influences health are scarce. Freiberg et al. (2019) were unable to identify any epidemiological studies on the effects of WTIS exposure. Such studies were also not found for the current literature review.

Kännälä, Toivo, and Toivonen (2017) have reviewed studies on the effects of infrasound on human participants, animals, and cells. In nearly all reviewed studies, infrasound was at least 100 dB, and results cannot be generalized to WTIS with much lower sound pressure levels. The measured outcomes also varied widely between studies, limiting conclusions on any given outcome.

As wind turbine noise always contains infrasound, finding no association between wind turbine noise and health would indicate no association between WTIS and health. Currently, large-scale epidemiological studies have not found an association between wind turbine noise exposure and self-reported symptoms of a broad range (Michaud et al., 2016; Turunen, Tiittanen, & Lanki, 2016), disease (Michaud et al., 2016; Poulsen et al., 2018a, 2018b, 2018c, 2019a; Turunen, 2017d), or adverse birth outcomes (Poulsen et al., 2018d). Freiberg et al. (2019) have concluded in their review that wind turbine noise exposure is not associated with stress, but that studies are mixed in their results regarding sleep disturbance, quality of life, and mental health problems.

Presently, the only established association between wind turbine noise and health is that wind turbine noise is annoying, and annoyance increases along with increasing sound pressure levels (review: Freiberg et al., 2019; review: Turunen, 2017b). The World Health Organization has therefore recommended limiting average wind turbine noise exposure to 45 dB (WHO Regional Office for Europe, 2018). Additionally, a recent prospective study found that the use of sleep medications and antidepressants seems to be associated with night-time outdoor wind turbine noise exposure, albeit not with indoor wind turbine noise exposure (Poulsen et al., 2019b). However, associations between wind turbine noise and health can be explained by factors other than infrasound, such as the clearly audible higher frequency components of wind turbine noise.

Still, methodological issues in wind turbine noise studies may limit conclusions on the health effects of wind turbine noise or lack thereof. Freiberg et al. (2019) report that only a quarter of the studies in their review were generalizable, and around half demonstrated sufficient reporting quality. Selection and information biases were also common in observational studies.

Moreover, it is possible that previous studies have not had the statistical power to detect associations between wind turbine noise and health. Only a small minority of people living near wind turbines are disturbed by them (e.g., Turunen et al., 2016), and this may reflect a subset of the population especially sensitive to WTIS. Carlile et al. (2018) and Lanki et al. (2017b) have proposed that the number of sensitive individuals may be so small that previous studies have not been able to detect an association between wind turbine noise and health. The proportion of participants exposed to high levels of WTIS in previous epidemiological studies may also have been insufficient for finding effects. The lead author of a series of studies on wind turbine noise and health (Poulsen et al., 2018a, 2018b, 2018c, 2018d, 2019a, 2019b) has cautioned in an interview that their study population exposed to the loudest wind turbine noise was small, limiting statistical power (Seltenrich, 2019). It cannot be concluded that wind turbine noise or infrasound does not affect health if studies with null findings have been underpowered.

1.6 Misassociating Wind Turbine Infrasound With Symptoms

Because WTIS has not been demonstrated to affect health, relating symptoms to WTIS has been proposed to be caused by individuals misassociating harm with WTIS. WTIS related symptoms may therefore be similar to environmental intolerances like multiple chemical sensitivity and electromagnetic hypersensitivity, where heterogeneous somatic symptom experiences seem to be explained by cognitive processes rather than environmental exposures (review: Van den Bergh, Brown, Petersen, & Witthöft, 2017). Two related processes by which symptoms can be misassociated with WTIS are symptom misattribution and the nocebo response.

Symptom misattribution occurs when pre-existing symptoms or ailments are believed to be caused by events unrelated to them (review: Faasse, 2019; review: Rubin et al., 2014). Experiencing symptoms — including the kind attributed to WTIS, such as headache, insomnia, fatigue, dizziness, and nausea — is incredibly common in the general population, with over 80 % reportedly experiencing at least one symptom in the recent past (Helldán & Helakorpi, 2015; Petrie, Faasse, Crichton, & Grey, 2014). It is also common that no obvious reason for experienced symptoms is found (review and meta-analysis: Haller, Cramer, Lauche, & Dobos, 2015). Opportunities for symptom misattribution to take place are therefore not rare.

Misattributing symptoms to WTIS may have increased after the spread of allegations that WTIS is harmful. Chapman et al. (2013) have argued that exposure to anti-wind farm groups presenting WTIS as a cause of health problems has driven some Australian residents to associate a wide variety of symptoms with nearby wind farms. Finnish wind farm and infrasound critical websites and social media discussions may have likewise spread symptom misattribution and anxiety related to wind farms in Finland. Misattributing pre-existing symptoms to unrelated factors, such as WTIS, can also facilitate the development of a nocebo response.

Nocebo, opposite to placebo, refers to negative experiences or outcomes which are elicited but not explained by the event they are attributed to (review: Faasse, 2019;

review: Petrie & Rief, 2019). Expectations are believed to be central to causing placebo and nocebo reactions, meaning that an individual has associated specific cues with specific outcomes. These associations can be the result of instructional or observational learning (e.g., media reports on health risks), conditioning (e.g., nausea due to previous food poisoning), as well as beliefs (e.g., perceived sensitivity to medicine). Once an individual expects WTIS to cause them harm, symptoms can arise when they believe they are exposed to it.

Anxiety may play a dual role in facilitating nocebo responses by causing physiological symptoms due to stress, such as chest pain, gastrointestinal distress, and irregular breathing, as well as a heightened awareness of threatening cues, often including anxiety symptoms themselves (review: Faasse, 2019). Therefore, both pre-existing anxiety and anxiety caused by an expectation of WTIS exposure could increase the likelihood of an individual experiencing symptoms that are then attributed to WTIS. As an absence of control over events may aggravate nocebo responses (review: Faasse, 2019), concerned individuals living near wind farms may also feel unable to escape the influence of WTIS, increasing their distress and symptom experiences.

A series of experimental studies provides support that the nocebo response may explain symptoms attributed to WTIS. A double-blind study found that symptom reports were not influenced by whether participants were exposed to infrasound or sham infrasound, but rather by an expectancy manipulation: participants who were shown a video suggesting that WTIS causes symptoms reported more symptoms than those who were informed that WTIS would not cause symptoms (Crichton, Dodd, Schmid, Gamble, & Petrie, 2014). The same effect was found using a stimulus with combined infrasound and audible wind turbine noise, with a negative expectation group reporting a worsening of symptoms and mood during noise exposure and a positive expectation group improvement in symptoms and mood (Crichton, Dodd, Schmid, Gamble, Cundy, & Petrie, 2014). Furthermore, an explanation of the nocebo effect was found to reduce symptom and mood reports elicited by a negative expectancy manipulation back to baseline levels (Crichton & Petrie, 2015). One study found that subjective noise sensitivity was related to higher annoyance and negative mood after wind turbine noise exposure, but only after framing wind turbine noise negatively; this suggests that expectations may play an even larger role in explaining symptoms than stable personality traits previously associated with noise annoyance (Crichton et al., 2015).

Tonin, Brett, and Colagiuri (2016) conducted a similar experimental study on infrasound and expectations. While their results regarding the effects of infrasound exposure and expectancy manipulation were inconclusive, the authors found that prior concern about the health effects of WTIS correlated with symptom reports.

Although the nocebo response may be significant in explaining symptoms and their severity, a nocebo reaction elicited during exposure to real or sham infrasound does not by itself rule out the possibility of physiological effects caused by infrasound. First, a nocebo or placebo reaction can conceivably be elicited for any event with a convincing expectancy manipulation. So, it is not especially noteworthy that a nocebo reaction can be elicited during sham infrasound. Second, expectations can influence symptom experiences regardless of whether an exposure or treatment has an independent physiological effect. For example, the degree of pain reduction by an analgesic drug is affected by whether a patient knows they are receiving the drug (review: Petrie & Rief, 2019).

Infrasound was not found to cause symptoms in the experimental studies investigating nocebo responses to WTIS. However, this could be the result of inadequate infrasound stimuli, as all the studies have been criticized for not using stimuli representative of actual wind turbine noise (Alamir et al., 2019; Tonin et al., 2016). For example, several studies used a 9 Hz tone to represent WTIS (Crichton, Dodd, Schmid, Gamble, Cundy, et al., 2014; Crichton et al., 2015; Crichton & Petrie, 2015), but WTIS is broadband. The effects of WTIS exposure cannot be inferred without the use of realistic WTIS stimuli. Experimental studies on the effects of WTIS would also be improved by knowingly including participants who feel that they are sensitive to WTIS and therefore have symptoms.

1.7 Aims of the Current Study

The objective of the current study is to investigate whether exposure to realistic wind turbine infrasound can be detected by individuals who live near wind farms and attribute experienced symptoms to wind turbines (“symptomatic individuals”). Their ability to detect WTIS will be compared with individuals who also live near wind farms but do not attribute symptoms to wind turbines (“asymptomatic individuals”). Based on this comparison it will be inferred whether symptomatic individuals are perceptually sensitive to WTIS and thus possibly susceptible to WTIS-induced symptoms. This objective will be explored from two perspectives:

(1) Do participants discriminate wind turbine noise with infrasound from wind turbine noise without infrasound, and is there a difference between symptomatic and asymptomatic individuals in discrimination ability? It is hypothesized that neither group can discriminate the presence of infrasound in wind turbine noise, as previous research suggests that WTIS is unlikely to be detectable.

(2) Does WTIS exposure cause stress, and is there a difference between symptomatic and asymptomatic individuals in the level of stress elicited by WTIS? Autonomic nervous system activity will be considered alongside self-reported stress to account for possible reactivity to WTIS that is difficult to consciously perceive. Corresponding with the first hypothesis, and as there is no direct evidence that WTIS could cause symptoms, it is hypothesized that WTIS exposure does not cause stress in either group.

A secondary objective is to investigate whether sham infrasound causes a nocebo response in symptomatic individuals, thus supporting the nocebo explanation of symptoms attributed to WTIS. This objective will be explored through the third research question:

(3) Does sham infrasound exposure cause stress, and is there a difference between symptomatic and asymptomatic individuals in the level of stress elicited by sham infrasound exposure? Based on previous studies suggesting that a nocebo response can be elicited in response to sham infrasound, sham infrasound is expected to increase stress in the symptomatic group. Stress is also expected to be higher in the symptomatic than the asymptomatic group after sham infrasound exposure, as the symptomatic group is presumably concerned about the health effects of infrasound while the asymptomatic group is not. No assumption is made about whether sham

infrasound elicits stress in the asymptomatic group, as an expectancy manipulation on the harmfulness of WTIS will not be included in the current study.

2 Methods

2.1 Participants

The study population comprised 24 participants, of whom 11 (7 females) were symptomatic and 13 (6 females) were asymptomatic controls. Participants within the symptomatic group attributed experienced symptoms to WTIS, whereas participants within the asymptomatic group did not. Symptomatic participants were on average 58.0 years old (range = 41–71), and asymptomatic participants were on average 55.3 years old (range = 30–72 years). Participant age was defined as age on the last experiment day. All participants reported living near a wind farm. The median self-reported distance to the nearest wind turbine was 4.0 kilometers (range = 1.0–30.0 km) in the symptomatic group and 4.3 kilometers (range = 0.6–11.0 km) in the asymptomatic group. The level of education was nearly identical between groups and ranged from elementary school to an academic degree in both. Most participants (21/24) had completed trade school or a higher level of education.

Participants were invited to participate in this study through an epidemiological survey study belonging to the same project (Maijala et al., 2020), wind power critical organizations Tuulivoima-Kansalaisyhdistys ry and Suomen Ympäristöterveys SYTe ry, local newspapers, and personal telephone calls. Participants contacted research nurses at the Finnish Institute of Occupational Health, who were responsible for conducting all participant instruction and data collection. Exclusion criteria were moderate or severe somatic disease, moderate or severe mental disorder, and hearing impairment. Eligible volunteers were sent a full briefing and consent form via mail. Participants signed the informed consent form before participating in the experiment. Participants were compensated for their travel expenses and offered lunch. Hotel accommodation was additionally compensated when required.

A total of 27 participants took part in the study. Due to difficulties in recruiting symptomatic participants, the final sample size of the study was smaller than planned. Three asymptomatic participants were excluded from all analyses based on their self-report of not living near a wind farm so that the symptomatic and asymptomatic groups had similar histories of exposure to wind turbine noise.

Participants were classified into the symptomatic or asymptomatic group based on their answer to the following survey question: “Do the following environmental exposures and situations cause you to feel ill or cause discomfort: Wind turbines”. Participants who answered *not at all* were classified into the asymptomatic group, and participants who answered *somewhat* (n = 3), *quite a lot* (n = 4), or *very much* (n = 3) were classified into the symptomatic group. One participant was reclassified into the symptomatic group based on positive answers to other survey questions related to wind turbine noise and health. The symptomatic group was sent an additional survey asking to specify whether audible sound, infrasound, or vibrations caused by wind farms causes them symptoms (Table A1). Most symptomatic participants (9/11) reported that wind turbine infrasound makes them feel ill or causes them discomfort.

The study was conducted in Finnish. Study materials have been translated into English for this report by the author. The study was conducted in accordance with the Declaration of Helsinki, and the ethical statement was obtained from the ethical board of the Helsinki University Hospital.

2.1.1 Symptoms Experienced by Participants

Participants were asked to rate how troubled they have been by 23 different symptoms in the past month and whether they believe each symptom is caused by wind farms (Table A2). The symptomatic group reported experiencing a greater number of symptoms than the asymptomatic group ($t(13) = -2.25$, $p = .04$, unequal variances assumed). Asymptomatic participants had experienced on average 5.38 different symptoms ($SD = 3.99$) in the past month, whereas symptomatic participants had experienced on average 11.20 different symptoms ($SD = 7.39$). The symptomatic group also reported greater severity of symptoms than the asymptomatic group ($t(11) = -2.46$, $p = .03$, unequal variances assumed). Mean symptom severity on a 5-point scale was 1.35 ($SD = 0.32$) in the asymptomatic group, whereas mean symptom severity was 2.03 ($SD = 0.83$) in the symptomatic group.

In the asymptomatic group, participants did not attribute any symptoms they had experienced from the list of 23 symptoms to wind farms. However, four of these participants were uncertain about whether one or more of their symptoms was caused by wind farms (answers *maybe* and *I do not know*). Within the symptomatic group, the proportion of experienced symptoms that were attributed to wind farms varied widely: five participants did not judge any of their symptoms from the list to be related to wind farms, whereas the rest attributed 16% to 86% of experienced symptoms to wind farms. Eight symptomatic participants were uncertain about whether one or more of their symptoms was caused by wind farms.

Most of the 23 symptoms were thought to be caused by wind farms by at least one symptomatic participant. This corresponds with the diverse range of symptoms attributed to WTIS as described in the academic literature and encountered in social media. The symptoms most often attributed to wind farms were tinnitus and fatigue or exhaustion.

2.2 Experiment Room and Sound System

Experiments were conducted at the Finnish Institute of Occupational Health research laboratory. The experiment room was a two-by-three meter, 2.22-meter-high airtight measurement chamber. Acoustic stimuli were presented using an active monitor loudspeaker (Genelec 8130A, Genelec, Inc., Iisalmi, Finland) for frequencies over 50 Hz and two loudspeaker drivers (Alpine SWR-1522D, Alpine Electronics of America, Inc., Torrance, California) with a directly coupled amplifier (Brüel & Kjær 2721, Brüel & Kjær Sound & Vibration Measurement, Nærum, Denmark) for frequencies under 50 Hz. The loudspeaker drivers were attached to the measurement chamber door and hidden from participants behind a curtain. Calibration signals with 20 Hz and 200 Hz tones were used to adjust acoustic stimuli to the original sound pressure level of corresponding wind turbine noise recordings. The total compensated frequency response was within ± 1.5 dB for frequencies between 0.27 Hz and 10 000 Hz.

A crosshair laser was used to position participants at a desk so that the location of the ears was equivalent among participants. Experiments were conducted with

Presentation software version 21.1 (Neurobehavioral Systems, Inc., Berkeley, California) on a standard Windows 10 workstation.

2.3 Wind Turbine Noise and Infrasound Stimuli

Wind turbine noise was recorded in Kurikka and Raahe as part of a long-term measurement campaign. Microphones were calibrated between 0.050 Hz and 20 000 Hz. Wind turbine noise emission was recorded approximately 200 meters away from the nearest wind turbine. Immission recordings were conducted outside and inside two residential properties located 1.5 and 1.6 kilometers away from the nearest wind turbine. Full details on the measurement locations and procedure can be found in the technical report by Maijala et al. (2020).

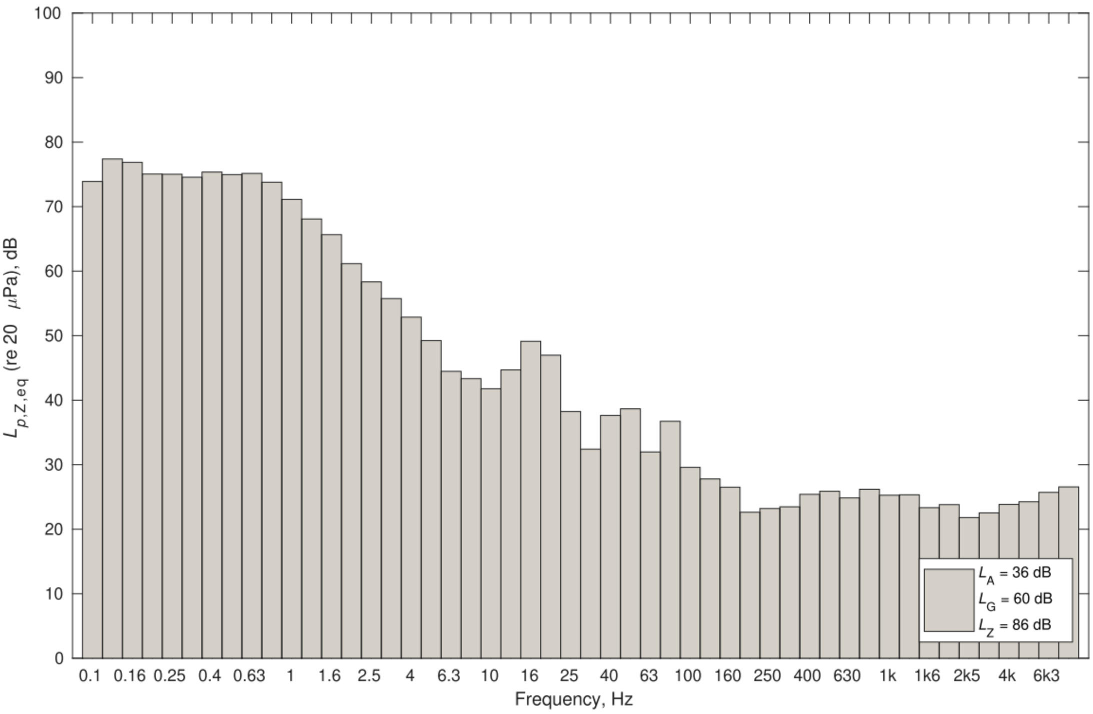
Wind turbine noise samples were picked to be used for stimuli based on the following criteria: First, the sample contained large amounts of infrasound, which was verified based on calculated sound pressure levels in the infrasound range and visual inspection of spectrograms. Second, the sample did not include unrelated noise such as bird song, traffic noise, thuds, or speech. Samples with minimal and maximal amplitude modulation were picked based on calculated levels of amplitude modulation.

Wind turbine noise stimuli used in the discrimination task (section 2.5.1) were created from ten wind farm (emission) samples, ten residential yard samples, and ten indoors samples. The linear sound pressure level was 91 dB (69–71 dBA) in wind farm samples, 77–82 dB (46–48 dBA) in yard samples, and 83–86 dB (34–38 dBA) in indoors samples. Stimulus duration was 10 seconds. Unfiltered stimuli were created along with 20 Hz and 100 Hz high-pass filtered versions. Filters were fourth-order infinite impulse response filters with a 0.5 dB passband ripple. Half of the wind farm and yard stimuli were filtered with the 20 Hz cutoff and half with the 100 Hz cutoff. For all indoors stimuli, only 20 Hz high-pass stimuli were created (Table 1). Two or three stimuli in the 20 Hz and 100 Hz high-pass wind farm and yard stimuli were based on samples with maximal amplitude modulation and the rest on samples with minimal amplitude modulation. Amplitude modulation was not controlled for indoors stimuli.

The WTIS stimulus used in the passive task with blinded WTIS exposure (section 2.5.2) was created from a 447-second wind turbine noise sample recorded inside the residential property in Raahe (Figure 1). A fourth-order infinite impulse response filter with a 20 Hz low-pass cutoff and 0.5 dB passband ripple was used to create the stimulus. Stimulus duration was 7.5 minutes.

Figure 1

Frequency Content for the Wind Turbine Infrasound Stimulus



Note. This figure presents the sound spectrum (i.e., linear sound pressure level of third-octave bands) of a wind turbine noise sample recorded inside a residential property. The property was located 1.5 kilometers away from the nearest wind farm and was abandoned by its residents because of wind turbine noise. The figure legend describes the overall sound pressure level of the sample (L_Z = linear; L_A = A-weighted). The wind turbine infrasound stimulus (≤ 20 Hz) for the passive task with blinded infrasound exposure was reproduced based on this sample. Reproduced with permission from the technical report *Infrasound Does Not Explain Symptoms Related to Wind Turbines* (Maijala et al., 2020).

Compensating inverse finite impulse response filters with lengths between 2^{14}-1 and 2^{18}-1 were used so that the frequency contents of all stimuli corresponded with recorded wind turbine noise sound pressure levels. 49 Hz low-pass and 51 Hz high-pass fourth-order infinite impulse response filters with a 0.5 dB passband ripple were used to present the correct frequency content at the separate low- and high-frequency channels of the sound system (2.2).

2.4 Stress Measures: Perceived Stress Inquiry and Electrodermal Activity

Participants' perceived stress was measured by asking participants to rate their level of stress ("How stressed do you feel at this moment?") on a scale of 0 (*no stress whatsoever*) to 10 (*extreme stress*). This inquiry was presented on a sheet of paper on which participants also wrote down their answer. Perceived stress was measured several times during the experiment day, as detailed in Figure 2.

Electrodermal activity (EDA) is a marker of sympathetic nervous system activity and is measured to investigate whether physiological arousal due to a stressor has occurred (Dawson, Schell, & Filion, 2016). EDA was recorded from the palmar side of the proximal phalanges of the index and middle fingers of the non-dominant hand. The participant washed their hands with water before isotonic sodium chloride electrode paste and silver/silver chloride electrodes were attached to recording sites. Continuous recordings (sampling rate 500 Hz) were conducted using a NeurOne EXG40 amplifier (Mega Electronics Ltd, Kuopio, Finland). Electrocardiography, respiration, electro-oculography, and electromyography were also recorded but are not included in the current report.

The cold pressor test was used to induce stress in participants (McRae et al., 2006) to ensure adequate sensitivity of EDA measurements to detect sympathetic arousal. Participants immersed their non-dominant hand in a bucket of 4–5 °C water for three minutes. Additionally, participants orally answered the perceived stress inquiry after one minute, two minutes, and three minutes of immersing their hand in the water.

2.5 Procedure

Participants completed several online questionnaires at home concerning demographic background information, general health, personality, symptoms, and attitudes related to wind farms. Participant classification into the symptomatic and asymptomatic groups and other participant information summarized in the previous sections are based on these questionnaires.

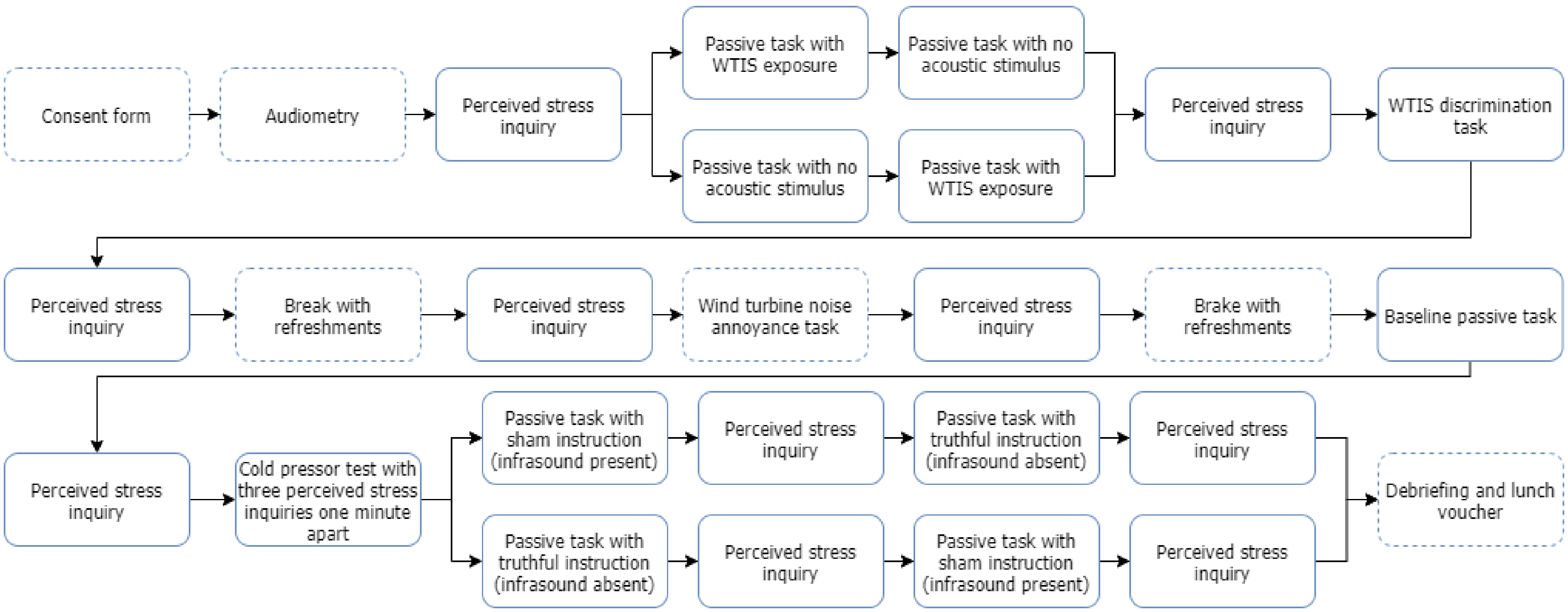
For each participant, the experiments outlined in Figure 2 were then conducted within a single session, lasting approximately four hours. Experiments were conducted 24.10.2019–07.02.2020. The research nurses who conducted the experiments were not aware of which group a participant belonged to.

Participants were screened for hearing loss in the frequency range 125–8000 Hz with an audiometer (Amplivox PC850, Amplivox, Birmingham, England) and given a copy of their audiogram. Three participants (one asymptomatic and two symptomatic) had hearing loss in both ears of 40 dB or more for frequencies higher or equal to 4000 Hz, 6000 Hz, and 8000 Hz, respectively. None of these participants were excluded from the study.

All participants participated in a wind turbine noise annoyance task, but results from this task are excluded from the current report. During this task, participants were asked to rate the level of annoyance elicited by various wind turbine noise samples and ocean beach sounds.

Figure 2

Course of the Experiment Day at the Research Laboratory



Note. Participants' perceived level of stress was inquired several times around experimental tasks and during the cold pressor test. Electrodermal activity was continuously recorded. The order of passive tasks was counterbalanced between participants. Data from the wind turbine annoyance task is not considered in the current report. WTIS = wind turbine infrasound. Image produced with diagrams.net.

2.5.1 Wind Turbine Infrasound Discrimination Task

A two-interval same–different forced-choice task was used to evaluate whether participants could discriminate wind turbine noise with infrasound from wind turbine noise without infrasound. As a positive control test (i.e., to ensure task validity), it was also investigated whether participants could discriminate wind turbine noise with low-frequency sound from wind turbine noise without low-frequency sound. Participants were expected to discriminate the presence of low-frequency sound if they understood task instructions (based on, for example, the experimental results of Yokoyama et al. (2014)). All trials consisted of two sequentially presented sound stimuli separated by 500 milliseconds of silence. Identical trials consisted of a stimulus pair with two identical unfiltered wind turbine noise stimuli, whereas unidentical trials consisted of a stimulus pair with an unfiltered wind turbine noise stimulus and its filtered version. In half of the unidentical trials, the unfiltered stimulus was presented first, and in half the filtered stimulus was presented first.

Participants were instructed to evaluate whether two sounds within a pair were the same or different. The participant was prompted to answer after the second stimulus was presented. Responses were collected with a standard keyboard with labeled response keys, and answers were given with the dominant hand. After the participant gave a response, there was a random delay of 200–400 milliseconds before the start of the next trial.

The discrimination task consisted of five blocks, each lasting approximately nine minutes. Each block contained identical and unidentical trials from five stimulus conditions: wind farm 100 Hz high-pass, wind farm 20 Hz high-pass, yard 100 Hz high-pass, yard 20 Hz high-pass, and indoors 20 Hz high-pass (Table 1). The order of the blocks and trials within the blocks was pseudorandomized. Participants were given the opportunity for a break between blocks. Participants practiced with three trials before the actual discrimination task.

Table 1

The Number of Wind Turbine Noise Stimuli and the Number of Trials for Stimulus Conditions in the Wind Turbine Infrasound Discrimination Task

Unfiltered stimuli	Stimuli	Identical trials	**Filtered stimuli**	Stimuli	Unidentical trials
Wind farm	10	20	Wind farm 100 Hz high-pass	5	10
			Wind farm 20 Hz high-pass	5	10
Yard	10	20	Yard 100 Hz high-pass	5	10
			Yard 20 Hz high-pass	5	10
Indoors	10	20	Indoors 20 Hz high-pass	10	20

Note. Stimuli were created from wind turbine noise samples so that one sample was used to create an unfiltered stimulus and a high-pass filtered stimulus. Participant responses on unidentical trials were compared with responses on identical trials with stimuli from corresponding wind turbine noise recording locations.

2.5.2 Blinded Wind Turbine Infrasound Exposure Experiment

To assess whether WTIS exposure elicits stress, participants underwent a 7.5-minute passive task during which they were blindly exposed to WTIS and a 5-minute passive task with no acoustic stimulus (i.e., no infrasound). During both tasks, the participant watched a muted nature video and was instructed to relax and avoid excessive movement. A research nurse informed the participant that their baseline physiological state would be recorded. The research nurses were unaware of whether infrasound was presented during either task. The order of the tasks was counterbalanced between participants.

2.5.3 Sham Infrasound Exposure Experiment

To assess whether sham infrasound exposure elicits stress, participants underwent three passive tasks. During all tasks, the participant watched a muted nature video and was instructed to relax and avoid excessive movement. The duration of all tasks was 5 minutes, and none contained an acoustic stimulus. The research nurses were unaware of whether infrasound was presented during any task.

The participant first underwent a baseline passive task, before which a research nurse informed the participant that their baseline physiological state would be recorded. Next, two tasks with an expectancy instruction were conducted. Preceding the passive task with a sham instruction, the participant was told “During the next task, infrasound will be played in the background”. Preceding the passive task with a truthful instruction, the participant was told “During the next task, infrasound will not be played in the background”. Instructions were also presented on a screen. The order of the tasks with an expectancy instruction was counterbalanced between participants.

2.6 Data Analyses

Statistical analyses were performed using R version 3.6.2 (R Core Team, 2019). Adequate distributions of continuous variables were ensured with visual inspections of density plots, and adequate linearity between continuous variables of interest was ensured with visual inspections of scatter plots. Visual inspections were performed separately for each group. Figures were produced with the ggplot2 package (Wickham, 2016).

Linear mixed-effects model (LMM) analyses were performed with the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) as an alternative to repeated measures analyses of variance to better account for unbalanced and missing data. All LMMs were random intercept models with participant as the random effect, with an unstructured variance-covariance structure, and were estimated using restricted maximum likelihood estimation. Experimental phase or condition and group were treated as fixed effects. The statistical significance of fixed effects was evaluated using the afex package (Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2020) with type III sums of squares and Satterthwaite approximation for degrees of freedom. Adequate normality of model residuals was evaluated with histograms. Fixed-effect estimates of all LMM analyses are presented in the appendix (Table A3 – Table A10).

2.6.1 Wind Turbine Infrasound Discrimination Ability

The perceptibility of infra- and low-frequency wind turbine noise was analyzed by calculating *d'*, a sensitivity measure based on signal detection theory (Macmillan & Creelman, 2005). The measure *d'* reflects a participant's ability to detect or discriminate stimuli, independent of their bias toward a particular response. *d'* was calculated for each participant within each stimulus condition by subtracting the *Z*-score of the hit rate (the proportion of *different* responses in unidentical trials, *H*) from the *Z*-score of the false alarm rate (the proportion of *different* responses in identical trials, *F*), so that:

$$d' = Z(H) - Z(F) , \tag{1}$$

where *Z* is the inverse of the standard normal cumulative distribution function.

If a participant cannot discriminate between identical and unidentical trials, their performance is at chance level, resulting in $d' = 0$ as $H = F$. If an unbiased participant answers correctly (correct rejection or hit) on 69% of trials, $d' = 1$. A negative *d'* indicates that a participant is systematically incorrect in their responses.

When discrimination ability was calculated separately for each wind turbine noise sample, a clear outlier ($d' = 2.40$) was observed in the indoors condition. The outlier was likely caused by a filtering artifact. One indoors sample was therefore removed from all analyses, and the presented results are based on nine indoors samples, not ten as presented in Table 1.

Participants' ability to discriminate wind turbine noise with infrasound from wind turbine noise without infrasound above chance level (research question 1) was first analyzed by performing one-sample *t*-tests for the mean *d'* of all discrimination task stimulus conditions. The false discovery rate of multiple comparisons was controlled (Benjamini & Hochberg, 1995) at $q \leq 0.05$. Differences in discrimination ability between groups were then analyzed with a LMM, where discrimination task stimulus condition and group were treated as fixed effects.

2.6.2 Preprocessing of Electrodermal Activity

EDA was preprocessed using Ledalab version 3.4.8 with MATLAB R2017b (The MathWorks, Inc., Natick, Massachusetts, United States). Continuous decomposition analysis (Benedek & Kaernbach, 2010) was used to extract peak onsets and peak amplitudes of skin conductance responses.

The mean number of skin conductance responses per minute and the mean amplitude of skin conductance responses were then calculated for each participant within tasks of the blinded wind turbine infrasound exposure experiment, the sham infrasound exposure experiment, and the cold pressor test. EDA could not be analyzed for up to two participants in each passive task condition due to technical difficulties, and missing data was not replaced. Peaks that occurred less than 0.5 seconds after the previous peak and peaks with an amplitude under 0.2 microsiemens were excluded. Possible remaining artifacts were not investigated.

To verify the sensitivity of EDA analyses to changes in stress or arousal, the number of skin conductance responses and the mean amplitude of skin conductance responses were compared between the cold pressor test and the baseline passive task with paired-samples *t*-tests.

2.6.3 Stress During Wind Turbine Infrasound Exposure

Whether WTIS exposure elicits stress (research question 2) was examined with three LMM analyses. First, the level of perceived stress before the first passive task was compared with perceived stress after the second passive task. Second, EDA during the passive task with WTIS exposure and during the passive task with no acoustic stimulus was compared. This analysis was performed separately for the mean number of skin conductance responses and the mean amplitude of skin conductance responses.

2.6.4 Stress During Sham Infrasound Exposure

Whether sham infrasound exposure elicits stress (research question 3) was examined with three LMM analyses. First, the level of perceived stress after the baseline passive task, after the passive task with a sham instruction of infrasound exposure, and after the passive task with a truthful instruction of no infrasound exposure was compared. Second, EDA during the baseline passive task, during the passive task with a sham instruction of infrasound exposure, and during the passive task with a truthful instruction of no infrasound exposure was compared. This analysis was performed separately for the mean number of skin conductance responses and the mean amplitude of skin conductance responses. The baseline passive task was included in analyses as some participants may distrust the instruction of no infrasound exposure, thus making the passive task with a truthful instruction a second sham infrasound condition.

By mistake, the passive task with a sham instruction was carried out twice with six participants. Therefore, data for these participants was missing for EDA during the passive task with a truthful instruction and for perceived stress after this condition. Missing data were not replaced, resulting in nine participants in each group for the truthful condition. For participants presented the sham instruction twice, only data from the first instructed passive task was analyzed. The order of the passive tasks with instruction remained counterbalanced, as participants who were presented the sham instruction task twice were supposed to be presented the sham instruction first and the truthful instruction second.

2.6.5 Time-Dependence of Perceived Stress

Based on visual inspection of the data, an additional analysis was carried out on the time-dependence of perceived stress throughout the whole course of the experiment day. Answers from all eleven perceived stress inquiries were analyzed by creating a time-variable with the order of the inquiries as its values. Whether there was an association between perceived stress and time of inquiry was then analyzed with a LMM where time and group were treated as fixed effects.

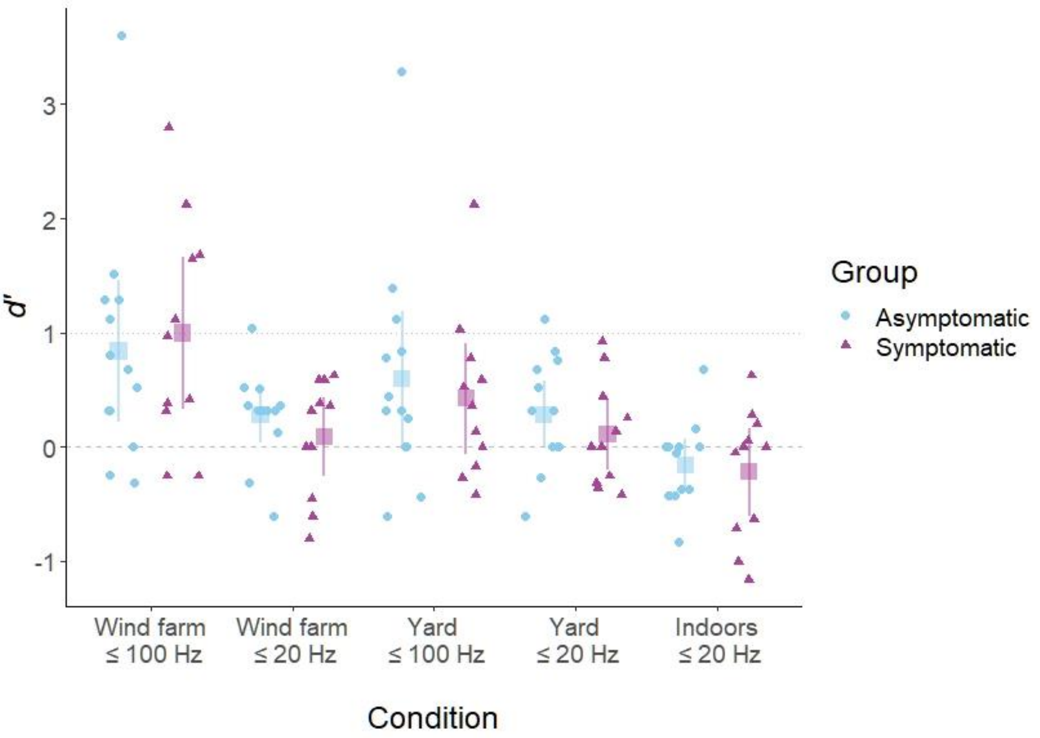
3 Results

3.1 Wind Turbine Infrasound Discrimination Ability

Participants’ ability to discriminate wind turbine noise with low-frequency sound from wind turbine noise without low-frequency sound was statistically significantly above chance level in both the wind farm and yard stimulus conditions ($q \leq 0.05$), satisfying the positive control test for the discrimination task. Average *d’* was 0.91 (*SD* = 0.99) in the wind farm 100 Hz high-pass stimulus condition, and average *d’* was 0.52 (*SD* = 0.86) in the yard 100 Hz high-pass stimulus condition. Participants were not found to discriminate wind turbine noise with infrasound from wind turbine noise without infrasound in the wind farm (*d’* = 0.19, *SD* = 0.45), yard (*d’* = 0.20, *SD* = 0.47), nor indoors (*d’* = -0.19, *SD* = 0.46) stimulus conditions after controlling the false discovery rate. Discrimination ability did not significantly differ between groups ($F(1,22) = 0.36$, $p = .56$), and there was no significant interaction between group and condition ($F(4,88) = 0.28$, $p = .89$).

Figure 3

Discrimination Ability in the Wind Turbine Infrasound Discrimination Task



Note. Discrimination ability (*d’*) for wind turbine noise with and without *(continued)*

(continued) low-frequency sound (≤ 100 Hz) and infrasound (≤ 20 Hz) is presented for each group. Means and 95 % confidence intervals are plotted over jittered observations for each participant. When $d' = 0$ (dashed line), performance is at chance level. When $d' = 1$ (dotted line), an unbiased participant answers correctly on 69% of trials.

One participant in the symptomatic group and one participant in the asymptomatic group had a considerably larger estimated discrimination ability in both the wind farm and yard low-frequency stimulus conditions than the rest of the group, as can be seen in Figure 3. The removal of these outliers did not influence the significance of the discrimination task results.

3.2 Perceived Stress

3.2.1 Perceived Stress During the Blinded Wind Turbine Infrasound Exposure Experiment

No significant difference was found comparing perceived stress before the first passive task with perceived stress after the second passive task ($F(1,22) = 2.94$, $p = .10$) or between groups ($F(1,22) = 0.35$, $p = .56$). Likewise, no significant interaction between group and condition ($F(1,22) = 0.09$, $p = .77$) was found. Figure 4 shows no apparent differences between groups or conditions.

3.2.2 Perceived Stress During the Sham Infrasound Exposure Experiment

No significant difference was found comparing perceived stress after the baseline passive task, after the passive task with a sham instruction of infrasound exposure, and after the passive task with a truthful instruction of no infrasound exposure ($F(2,41) = 0.08$, $p = .92$). There was also no significant interaction between condition and group ($F(2,41) = 0.01$, $p = .99$). However, there was a significant main effect of group ($F(1,23) = 11.92$, $p < 0.01$). Based on LMM fixed-effect estimates (Table A5), perceived stress on a scale of 0 to 10 was, on average, approximately 2 points higher in the symptomatic group than in the asymptomatic group after all three tasks.

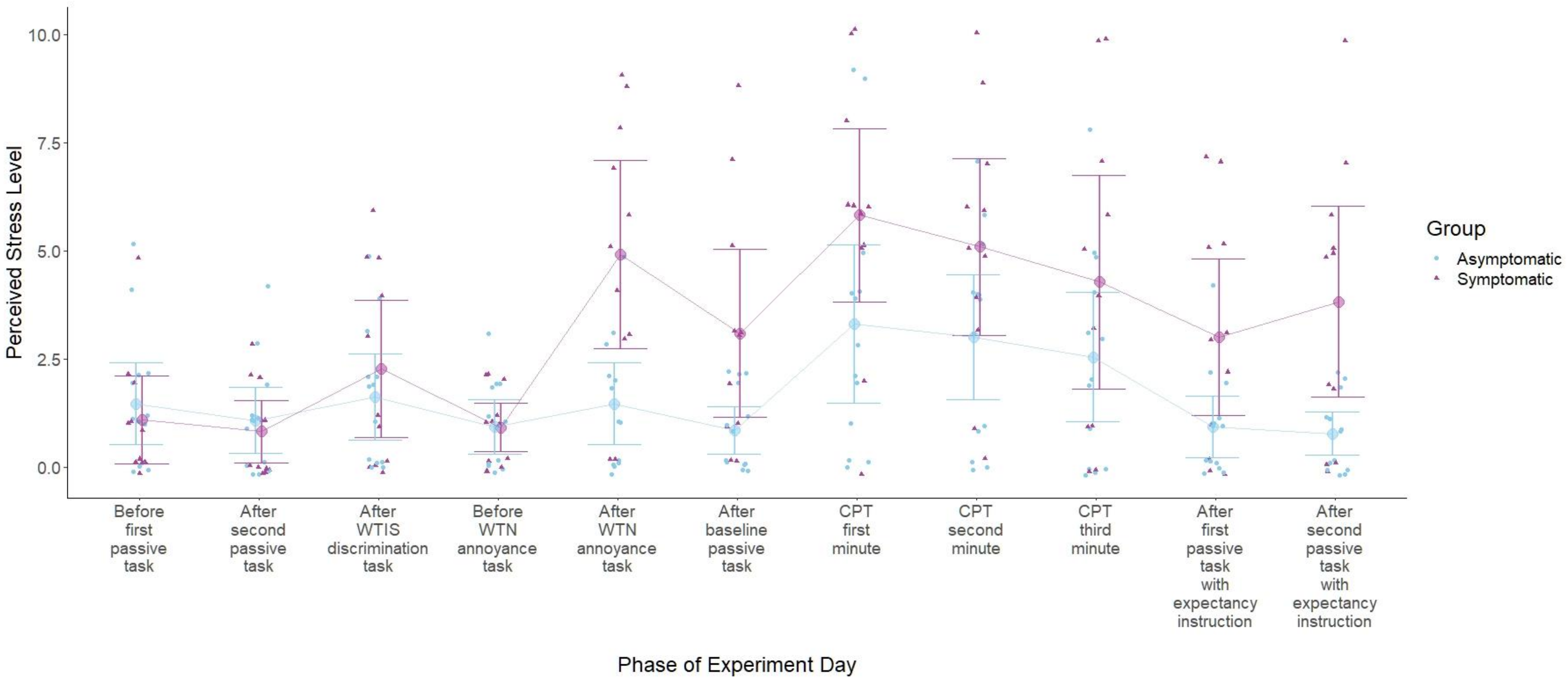
3.2.3 Time-Dependence of Perceived Stress

Across the whole course of the experiment day, a significant interaction was found between time and group in predicting perceived stress ($t(238) = 3.73$, $p < .001$). As can be seen from Figure 4 and LMM fixed-effect estimates (Table A6), perceived stress increased more over time in the symptomatic group than in the asymptomatic group. The two groups reported similar stress levels until the wind turbine noise annoyance task. From there onward, participants in the symptomatic group generally reported greater stress than participants in the asymptomatic group.

One asymptomatic participant reported a stress level of 0 for all eleven perceived stress inquiries. The removal of this participant did not influence the significance of the results in sections 3.2.1–3.2.3.

Figure 4

Results of the Perceived Stress Inquiry Across the Course of the Experiment Day



Note. Participants were exposed to WTIS during the first or second passive task. During the passive tasks with an expectancy instruction, participants were given a sham instruction of infrasound exposure and a truthful instruction of infrasound being absent. Means and 95 % confidence intervals are plotted over jittered observations for each participant. WTIS = wind turbine infrasound; WTN = wind turbine noise; CPT = cold pressor test.

3.3 Electrodermal Activity

The positive control test for the sensitivity of EDA-measurements to detect changes in stress or arousal was partially satisfied: The number of skin conductance responses per minute was larger during the cold pressor test compared with the baseline passive task ($t(21) = -6.08$, $p < .001$), but a statistically significant difference was not found for the mean amplitude of skin conductance responses ($t(21) = -1.87$, $p = .08$). Medians and ranges of EDA results for each task are reported in Table 2.

Table 2

Number of Participants Included in Electrodermal Data Analyses, the Median Number of Skin Conductance Responses Per Minute, and the Median Mean Amplitude of Skin Conductance Responses for Experimental Tasks

Task	Participants	Median (range) number of SCRs	Median (range) mean amplitude of SCRs (µS)
Passive task with WTIS exposure	23	1.73 (0.13–19.20)	0.61 (0.22–2.25)
Passive task with no acoustic stimulus	21	4.60 (0.20–20.20)	0.69 (0.24–2.72)
Baseline passive task	22	4.80 (0.40–27.60)	0.58 (0.27–3.04)
Cold pressor test	24	20.83 (5.33–54.33)	1.0 (0.24–2.03)
Passive task with truthful instruction	18	4.60 (0.20–34.20)	0.68 (0.31–1.65)
Passive task with sham instruction	23	4.40 (0.20–27.40)	0.61 (0.23–2.07)

Note. Electrodermal activity across all participants. Distributions of the results were also inspected separately for each group (not shown). For almost all tasks, the mean number of skin conductance responses per minute and the mean amplitude of peaks were skewed to the right in both groups. The exception was the mean amplitude of peaks in the passive task with a sham instruction, which was uniformly distributed in the symptomatic group. SCR = skin conductance response; µS = microsiemens; WTIS = wind turbine infrasound.

3.3.1 Electrodermal Activity During the Blinded Wind Turbine Infrasound Exposure Experiment

No statistically significant differences in EDA were found between the passive task with WTIS exposure and the passive task with no acoustic stimulus or between groups in either mean peak amplitude or the number of skin conductance responses per minute (Table 3).

Table 3

Electrodermal Activity in the Blinded Wind Turbine Infrasound Exposure Experiment: Analyses of Variance for the Mean Peak Amplitude of Skin Conductance Responses and for the Number of Skin Conductance Responses Per Minute

Effect	*df*	*F*	*p*
MEAN PEAK AMPLITUDE			
Group	1, 22	1.40	.25
Passive task condition	1, 18	0.22	.64
Passive task condition × Group	1, 18	0.12	.73
NUMBER OF SCRs PER MINUTE			
Group	1, 22	0.03	.87
Passive task condition	1, 19	0.68	.42
Passive task condition × Group	1, 19	0.47	.50

Note. Results are based on linear mixed-effects models (Table A7 and Table A8). SCR = skin conductance response.

3.3.2 Electrodermal Activity During the Sham Infrasound Exposure Experiment

No significant differences in EDA were found between the baseline passive task, the passive task with a sham instruction of infrasound exposure, and the passive task with a truthful instruction of no infrasound exposure or between groups in either mean peak amplitude or the number of skin conductance responses per minute (Table 4).

Table 4

Electrodermal Activity in the Sham Infrasound Exposure Experiment: Analyses of Variance for the Mean Peak Amplitude of Skin Conductance Responses and for the Number of Skin Conductance Responses Per Minute

Effect	*df*	*F*	*p*
MEAN PEAK AMPLITUDE			
Group	1, 21	0.03	.86
Passive task condition	2, 39	0.57	.57
Passive task condition × Group	2, 39	1.17	.32
NUMBER OF SCRs PER MINUTE			
Group	1, 21	0.02	.89
Passive task condition	2, 37	0.04	.96
Passive task condition × Group	2, 37	0.03	.97

Note. Results are based on linear mixed-effects models (Table A9 and Table A10). SCR = skin conductance response.

4 Discussion

The primary aim of the current study was to investigate whether individuals who live near wind farms and attribute symptoms to wind turbine infrasound can detect WTIS, thus indicating a possible susceptibility to WTIS-induced symptoms. As hypothesized, no evidence was found for perceptual sensitivity to WTIS: On average neither symptomatic participants nor asymptomatic controls were found to discriminate wind turbine noise with infrasound from wind turbine noise without infrasound, and there was no indication that blinded WTIS exposure elicits stress in either group. These results are consistent with the prevailing literature, which suggests that WTIS is unlikely to be detectable (review: van Kamp & van den Berg, 2018; Yokoyama et al., 2014) or to influence the prevalence of symptoms or diseases (Michaud et al., 2016; Poulsen et al., 2018a, 2018b, 2018c, 2019a; Turunen, 2017d; Turunen et al., 2016).

As presumably the first laboratory study to focus on the effects of WTIS exposure on symptomatic individuals, the current study provides essential information on whether WTIS could explain symptom reports attributed to it. Crucially, the results do not support the suggestion that symptomatic individuals would be more sensitive or sensitized to WTIS compared with asymptomatic individuals. Symptom experiences associated with WTIS are therefore likely to be explained by factors other than the occurrence of WTIS in residential areas.

A secondary aim of the current study was to investigate whether sham infrasound exposure elicits a nocebo response, particularly in symptomatic individuals, which could explain symptoms attributed to WTIS. Contrary to what was hypothesized, no evidence was found for a nocebo response that would be indicated by changes in autonomic arousal or perceived stress after a sham instruction of infrasound exposure. These results differ from previous experimental evidence indicating that expectations on the harmfulness of WTIS determine responses to sham infrasound (Crichton, Dodd, Schmid, Gamble, & Petrie, 2014) and to combined infrasound and audible wind turbine noise (Crichton, Dodd, Schmid, Gamble, Cundy, & Petrie, 2014; Crichton et al., 2015; Crichton & Petrie, 2015).

The results of Tonin et al. (2016) are similar to those of the current study in that sham infrasound was not found to elicit a nocebo response, but prior concern about the health effects of infrasound was associated with the number and intensity of reported symptoms in general. Likewise, in the current study it was found that symptomatic participants, who attributed symptoms to WTIS, reported more numerous and intense symptoms than asymptomatic participants in the pre-experiment questionnaire. Symptomatic participants also reported higher levels of stress than asymptomatic participants during the experiment day. These results suggest that dispositional factors might be associated with misattributing symptoms to WTIS, as discussed in section 4.3.

4.1 Perceptibility of Wind Turbine Infrasound and Low-Frequency Noise

Based on the results of the wind turbine infrasound discrimination task (Figure 3), it might be speculated whether some individuals can detect WTIS even though average discrimination ability was not found to differ from chance level. The sensitivity measure *d′* is an estimate of performance ability (Macmillan & Creelman, 2005). As such, the measured discrimination ability of an individual participant is not highly reliable when it is calculated based on a small number of stimulus repetitions as in the current study. Single observations of participants whose discrimination ability is above chance level can therefore not be meaningfully scrutinized. Confidence intervals for WTIS discrimination ability were also well below *d′* = 1. Consequently, it can be concluded that WTIS is likely to be challenging to detect even for sensitive individuals with the lowest detection thresholds. Yokoyama et al. (2014) have similarly concluded that WTIS is hardly audible or sensible based on their experimental results.

Interestingly, Nguyen, Hansen, Zajamsek, Micic, and Catcheside (2019) have presented in a conference paper that self-reported noise-sensitive individuals could detect whether infrasound was present in wind turbine noise. The methods of their pilot study were similar to the discrimination task of the current study, including the use of the sensitivity measure *d′*. The estimated average WTIS discrimination ability of noise-sensitive participants was not higher than of participants in the current study. Instead, the finding that noise-sensitive individuals could discriminate WTIS above chance level is likely explained by smaller variance in observed discrimination ability and not adjusting significance levels for multiple comparisons. It could therefore still be concluded that WTIS is at most challenging to detect. Furthermore, as WTIS exposure in the current study was not found to elicit changes in perceived stress or in autonomic arousal, health effects of WTIS remain doubtful.

Perceiving low-frequency wind turbine noise above 20 Hz and misinterpreting it as infrasound is more plausible than the perception of WTIS. First, the perceptibility of low-frequency wind turbine noise has been demonstrated by Yokoyama et al. (2014) and the current study. Yokoyama et al. (2014) found that wind turbine noise below

25 Hz could be detected by approximately half of participants when the wind turbine noise had a high sound pressure level that can occur close to wind farms (55 dBA). Most participants could detect wind turbine noise below 63 Hz even at the lowest sound pressure level of wind turbine noise presented (27 dBA), which is lower than wind turbine noise in the current study (34–38 dBA indoors). Yokoyama et al. (2014) also found that frequencies above 63 Hz contribute to the perceived loudness of wind turbine noise.

Second, Pedersen, Moller, and Waye (2008) have found that the detection of infrasound did not explain any investigated cases of low-frequency noise complaints, while noting that complainants may not distinguish low-frequency sound above 20 Hz from infrasound below 20 Hz. Therefore, symptomatic individuals living near wind farms may be annoyed by perceptible low-frequency wind turbine noise which they inaccurately call infrasound. In the current study, approximately half of the symptomatic participants who attributed a feeling of illness or discomfort to infrasound also attributed it to audible wind turbine noise and vibrations caused by wind turbines (Table A1), suggesting that symptomatic individuals may not precisely identify the source of their discomfort.

Several countries have similar limits for low-frequency noise (Finnish Ministry of Social Affairs and Health, 2015; Moorhouse, Waddington, & Adams, 2005), and compliance to these limits is justified as low-frequency noise can be highly annoying (review: Alamir et al., 2019). The World Health Organization also recommends limiting average wind turbine noise levels to 45 dB to limit annoyance caused by wind turbine noise in general (WHO Regional Office for Europe, 2018). In comparison, average wind turbine noise was measured to be 75 dB and 67 dB inside the noise recording residences of the current study (Maijala et al., 2020).

However, the symptomatic and asymptomatic groups of the current study were not found to differ in their response to WTIS exposure or in their ability to discriminate wind turbine noise with and without infrasound or low-frequency noise. Furthermore, stress is the mechanism through which noise could theoretically induce symptoms (section 1.4.1), but only one symptomatic participant attributed stress to wind farms in the pre-experiment questionnaire (Table A2). Therefore, it can be concluded that neither the perception of WTIS nor the perception of low-frequency wind turbine noise seems to cause the heterogeneous somatic symptoms of symptomatic individuals.

4.2 No Nocebo Response to Sham Infrasound

Sham infrasound exposure was not found to elicit a nocebo response in the symptomatic participants of the current study, contrary to what was hypothesized. This is possibly explained by a weakness in the design of the study, which is that the cold pressor test was conducted between the baseline passive task and the passive tasks with an expectancy instruction. As reactions to the current situation are influenced by the relative (un)pleasantness of the preceding situation (Leknes et al., 2013), participants may have experienced the passive tasks with instruction as relatively unstressful compared to the intensity of the cold pressor test. This may have attenuated observable nocebo responses to sham infrasound.

However, it is noteworthy that some symptomatic participants reported experiencing no or minimal levels of stress during the passive tasks with an expectancy instruction. It is possible that these participants were aware of previous nocebo studies on sham infrasound, as information about them has circulated in online discussion forums, and guessed correctly that the instruction of infrasound exposure was false. Some symptomatic participants reported higher stress after the truthful instruction of no infrasound exposure than after the sham instruction of infrasound exposure, which suggests that they may have interpreted the instructions to mean their opposite. Another possibility is that participants did not report increased stress as they did not perceive low-frequency wind turbine noise that could be misinterpreted as infrasound, thus also distrusting the expectancy instructions. The strongest expectations of infrasound exposure and an increased focus on noise-elicited symptoms may have occurred during the wind turbine noise annoyance task, as perceived stress was relatively high in the symptomatic group after this experiment.

Still, not all of the symptomatic participants of this study may have associated WTIS with symptoms so strongly that the suggestion of infrasound exposure would elicit a nocebo response. This possibility is supported by the pre-experiment questionnaire finding that approximately half of the symptomatic participants were not certain that wind turbines caused any of their symptoms experienced in the last month. Uncertainty about whether WTIS is causing experienced symptoms is also likely based on the finding that individuals with medically unexplained somatic symptoms often consider several possible causes when explaining them and rarely attribute symptoms solely to the environment (Hiller et al., 2010). Unlike previous nocebo studies on sham infrasound, the expectancy instruction of the current study did not suggest that infrasound exposure is harmful. Thus, baseline uncertainty about whether WTIS causes symptoms was likely unchanged, reducing the likelihood of a nocebo response to sham infrasound. It may be that of the minority of individuals who suspect that WTIS is harmful, few strongly attribute symptoms to WTIS. If so, the nocebo response may generally not cause the symptoms attributed to WTIS.

4.3 Dispositional Influences on Symptom Experience and Symptom Misattribution

The symptomatic participants of the current study were found to report generally higher levels of perceived stress during the experiment day than asymptomatic participants. However, no differences in electrodermal activity between groups were found. A possible reason for this discrepancy is that EDA measurements were insensitive to subtle changes in stress, as discussed in section 4.4. However, the covariance between self-reports and physiological measures of stress is known to be low, with self-reports being influenced by various factors such as perceived context, individual differences in interoception, and the interpretation of bodily states (review: Epel et al., 2018). In fact, it has been proposed that peripheral physiological input, such as of the level of autonomic nervous system activity, is not necessary for symptom experience (Van den Bergh, Witthöft, Petersen, & Brown, 2017).

The co-occurrence of attributing symptoms to WTIS, increased symptom reporting, and generally higher self-reported stress in the symptomatic participants of the current study is unsurprising, given that several vulnerability traits could explain an association between them. These traits include proneness to somatosensory amplification, recently specified as somatic threat sensitivity (review: Köteles &

Witthöft, 2017), negative affectivity (Leising, Grande, & Faber, 2009; review: Van den Bergh, Brown, et al., 2017), and anxiety proneness (review: Faasse, 2019; review: Van den Bergh, Witthöft, et al., 2017). These traits are theoretically and empirically related and can be summarized as reflecting an increased perception of both internal and external harmful events (Köteles & Doering, 2015; review: Köteles & Witthöft, 2017; review: Van den Bergh, Witthöft, et al., 2017). This disposition is likely related to a tendency to emphasize top-down predictions or priors concerning aversive experiences, so that the experience of symptoms can occur independently from the actual peripheral physiological state of the body and the effects of (or lack thereof) external stimuli (review: Köteles & Witthöft, 2017; review: Van den Bergh, Brown, et al., 2017; review: Van den Bergh, Witthöft, et al., 2017).

Furthermore, as experiences of undesirable symptoms increase, so may the pressure to explain them. Given that the extent of pre-existing symptoms seems to predict whether symptoms are attributed to environmental factors (review: Rubin et al., 2014), symptomatic individuals are likely more prone to associate their symptoms with unrelated environmental factors than asymptomatic individuals who experience significantly fewer symptoms in general.

Although symptom misattribution was not directly investigated in the current study, the increased reporting of symptoms and stress in the symptomatic group suggests it may explain why some people relate symptoms to WTIS. Symptom misattribution also seems plausible based on the observation that many symptomatic participants were uncertain about whether a symptom was caused by wind turbines or not, and so seemed unable to pinpoint the reason for their symptoms. Likewise, symptomatic participants might have had difficulty distinguishing the cause of their symptoms given that they attributed adverse effects to several consequences of wind turbine operation, not just infrasound. Symptom misattribution could also explain why such a wide variety of symptoms are associated with WTIS; The types and causes of pre-existing symptoms might differ within and among individuals but be misattributed to the same factor.

Tinnitus was one of the symptoms most often attributed to wind turbines by symptomatic participants. Endogenous tinnitus may be misinterpreted as external low-frequency noise (Pedersen et al., 2008), and thus tinnitus may be falsely attributed to wind turbines. The other symptom most often attributed to wind turbines was fatigue or exhaustion. As fatigue and tiredness are some of the most common symptom complaints in the general population (Koponen, Borodulin, Lundqvist, Sääksjärvi, & Koskinen, 2018; Petrie et al., 2014), they are symptoms which may be likely misattributed to unrelated environmental factors.

If cognitive processes underlie an individual's symptom experience, it is important for the treatment of symptoms to acknowledge that symptom experiences are real and to be taken seriously. Van den Bergh, Brown, et al. (2017) have suggested a compelling treatment strategy for medically unexplained symptoms based on a model of how top-down cognitions can give rise to symptoms. The strategy includes psychoeducation about the association between expectations and symptoms, disconfirming prior beliefs, and improving interoceptive accuracy. These methods might be applicable in alleviating symptoms or consequential worry associated with WTIS.

4.4 Strengths and Limitations of the Current Study

The current study includes several notable strengths. As study participants included individuals who live near wind farms and attribute symptoms to WTIS, possible associations between perceptual sensitivity to WTIS and symptoms could be studied more directly than in previous studies. Research questions were also investigated with multifaceted methods. This study included both an active WTIS discrimination task and a passive task with WTIS exposure. The non-focused passive task may correspond with typical responses to at-home WTIS exposure more accurately than focused listening to sound, as proposed by Alamir et al. (2019), while the active discrimination task gave a more accurate estimate of WTIS perceptibility. When investigating the level of stress during WTIS exposure and during sham infrasound exposure, both self-reported perceived stress and autonomic nervous responses were considered.

The experimental setup and stimuli are also noteworthy for their ecological validity. Realistic wind turbine noise and infrasound were reproduced based on representative long-term recordings of wind turbine noise and a sophisticated sound system that could produce infrasound down to 0.27 Hz. Sound was presented with loudspeakers, causing the whole body to be exposed to WTIS. Although the ear is likely the most sensitive organ to infrasound (Landström et al., 1983), whole-body exposure ensures ecologically valid exposure compared with presenting stimuli through headphones. Finally, WTIS levels indoors may not be predictable from WTIS levels outdoors due to building resonances and differential attenuation of low and high frequencies of sound (review: Carlile et al., 2018). By including wind turbine noise samples from inside a residential building in the WTIS discrimination task and in the passive task with blinded WTIS exposure, it could be evaluated whether WTIS might be detected indoors but not outdoors.

The conclusions of this study are limited to the detection of short-term exposure to WTIS and to wind turbine noise up to 91 dB (71 dBA). While no evidence was found for responsivity to blinded WTIS exposure, findings cannot be generalized to WTIS with higher sound pressure levels than presented in Figure 1. If higher WTIS levels were to be found in residential areas, the possibility of WTIS detection could not be dismissed based on the results of this study. Additionally, conclusions on non-auditorily mediated health effects from long-term WTIS exposure cannot be drawn from this study.

However, wind turbine noise recordings used for stimuli were measured up to 1.6 kilometers from the nearest wind farm, while the median self-reported residency distance to the nearest wind farm was 4 kilometers (range 1.0–30.0 km) in the symptomatic group. This implies that the sound pressure level of stimuli was adequate for assessing whether symptomatic individuals react to WTIS in their homes. Evidence of sensitization to WTIS due to long-term exposure was also not found.

It could be argued that a WTIS exposure time of 7.5 minutes during the passive task of this study was short even for a study investigating the effects of short-term exposure to WTIS (Tonin et al., 2016). However, there was ample time for the detection of infrasound to occur based on infrasound detection experiments (Burke, Hensel, Fedtke, Uppenkamp, & Koch, 2019; Friedrich, Joost, Fedtke, & Verhey, 2020), and autonomic and affective responses to sound exposure occur well under 30 seconds (Bradley & Lang, 2000; Hume & Ahtamad, 2013; Park, Lee, & Jeong, 2018). Likewise, a stimulus duration of 10 seconds, which was used in the wind turbine infrasound discrimination task, is enough for the detection of 5 Hz tones (Burke et al., 2019; Friedrich et al., 2020) and 2.5 Hz tones (Kuehler et al., 2015) to occur.

EDA measurements may not have been sensitive enough for the detection of subtle autonomic nervous system responses to WTIS exposure or to sham infrasound, as the mean amplitude of skin conductance responses was not statistically different comparing the cold pressor test with the baseline passive task. A possible weakness in the analysis of EDA was averaging responses over whole experimental blocks, most of which were 5 minutes long. As EDA responses have been found to become attenuated as noise exposure continues (Park et al., 2018), averaging responses over long periods would diminish differences between experimental conditions if responses to WTIS only occurred at the beginning of the exposure. However, reactivity to WTIS was in no way indicated by the results.

A commonly occurring weakness in statistical inference is also present in the current study. In this study, it was hypothesized that WTIS is not detectable, that WTIS exposure does not elicit stress, and that there are no differences between symptomatic and asymptomatic participants in responses to WTIS. As evidence for lack of effects was of interest, making inferences based on frequentist equivalence testing or Bayesian methods would have been more appropriate than conducting traditional null hypothesis significance testing (Lakens, 2017). Determining thresholds that dictate whether effects are present was challenging, resulting in the use of traditional significance testing. Despite this weakness, visual inspections of the results suggest no considerable effects where none were hypothesized. This adds confidence to conclusions that WTIS is unlikely to be detected by symptomatic individuals and that there is no difference in perceptual sensitivity to WTIS between symptomatic and asymptomatic individuals.

4.5 Future Directions

The reason for attributing symptoms to wind turbines could be different between individuals, and the small sample size of this study was insufficient to uncover effects that would only occur in some symptomatic individuals. In theory, one individual's symptoms could be explained by the nocebo response, another's by a low auditory threshold for detecting infrasound or low-frequency noise, and a third's by inner ear abnormalities which cause dizziness or nausea due to noise exposure. Future studies on wind turbine related symptoms might therefore focus on individuals who experience specific symptoms to ensure adequate statistical power in evaluating their cause. These studies could also expose participants to WTIS over a longer duration than used in the current study to better exclude the possibility of reactivity to WTIS.

Several factors within an individual may also influence wind turbine related symptoms. For example, someone could be disturbed by audible features of wind turbine noise, such as low-frequency sound, while simultaneously misattributing various symptoms to WTIS. It should be recognized that finding one explanation for why symptoms are attributed to wind turbines does not necessarily rule out other causes. Therefore, future studies could attempt to find explanations for wind turbine related symptoms in an individual while excluding other possible causes of their symptoms, similar to the study of low-frequency noise complaints by Pedersen et al. (2008).

4.6 Conclusions

The current study investigated responses to realistic wind turbine infrasound in individuals who feel that wind turbines cause them discomfort or to feel ill. These individuals were not found to be perceptually sensitive to WTIS compared with controls who did not attribute symptoms to wind turbines, and thus no evidence was found for a mechanism through which WTIS could induce symptoms.

Physiological reactions to WTIS exposure remain a doubtful cause of symptoms attributed to WTIS considering the results of this study, previous literature on the perceptibility and health effects of wind turbine noise, and the plausibility of mechanisms by which WTIS has been proposed to cause symptoms. Symptom attributions appear more likely to be explained by cognitive processes such as symptom misattribution or by disturbance caused by clearly perceptible consequences of wind turbine operation such as audible low-frequency noise.

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Appendix

Table A1

Symptom Attributions to Specific Consequences of Wind Turbine Operation

Symptomatic participant	Audible noise	Infrasound	Vibrations
A	0	2	0
B	3	0	0
C	3	“Cannot say”	“Cannot say”
D	2	“Probably 2”	“Probably 1”
E	3	3	2
F	3	3	1
G	0	3	2
H	1	2	0
I	0	3	2
J	1	2	0
K	3	3	3

Note. The symptomatic group was asked to specify whether audible sound, infrasound, or vibrations caused by wind farms makes them feel ill or causes them discomfort. Answers of each participant are presented, with 0 meaning *not at all*, 1 meaning *somewhat*, 2 meaning *quite a lot,* and 3 meaning *very much*.

Table A2

Median Severity of Each Symptom by Group and Number of Participants who Attributed a Given Symptom to Wind Farms

Symptom	Asymptomatic	Symptomatic	Number of wind farm attributions
1. Headache	2	2.5	2
2. A feeling of weakness or dizziness	1	2	2
3. Heart and chest pains	1	1	2
4. Lower back pain	2	1	1
5. Nausea/digestive issues	1	1.5	2
6. Muscle pain	2	2.5	1
7. Breathing difficulties	1	1	0
8. Hot and cold flashes	1	1	1
9. Prickling or numbness in some part of the body	1	2	1
10. The feeling of a lump in your throat	1	1	0
11. A feeling of weakness in different parts of the body	1	1	0
12. A feeling of weight in the arms and legs	1	1	1
13. Constant pains and aches	1	1.5	2
14. Tinnitus	1	3.5	5
15. Pressure in the ears	1	1.5	3
16. Arrhythmia	1	1	2
17. Rash, itching of the skin	1	1	0
18. Urinary issues	1	1.5	1
19. Fatigue or exhaustion	1	3	5

(Continued)

Table A2 *(Continued)*

Symptom	Asymptomatic	Symptomatic	Number of wind farm attributions
20. Nightmares	1	1	0
21. Difficulty falling asleep	1	3	3
22. Anxiety	1	1.5	1
23. Stress	1	2	1

Note. Participants were asked to answer the following question on a scale of 1 to 5 (1 meaning *not at all*, 2 meaning *fairly little*, 3 meaning *somewhat*, 4 meaning *quite a lot*, and 5 meaning *very much*): "The following is a list of problems and ailments that people experience from time to time. After reading each question carefully, choose the answer option which best describes how much the symptom in question has troubled or worried you in the last month (30 days)". Participants were also asked "For each symptom or ailment below, respond whether you think it is caused by a wind turbine" with the answer options *yes*, *no*, *maybe*, and *I don't know*. The number of wind farm attributions corresponds to the number of *yes* answers among all participants.

Table A3

Linear Mixed-Effects Model Estimates of Fixed Effects for Discrimination Ability (d') in the Wind Turbine Infrasound Discrimination Task

Effect	Estimate	Standard Error
Intercept: Wind farm ≤ 100 Hz	0.84	0.19
Symptomatic group	0.16	0.29
Wind farm ≤ 20 Hz	-0.56	0.26
Yard ≤ 100 Hz	-0.25	0.26
Yard ≤ 20 Hz	-0.56	0.26
Indoors ≤ 20 Hz	-1.00	0.26
Symptomatic group : Wind farm ≤ 20 Hz	-0.34	0.39
Symptomatic group : Yard ≤ 100 Hz	-0.32	0.39
Symptomatic group : Yard ≤ 20 Hz	-0.33	0.39
Symptomatic group : Indoors ≤ 20 Hz	-0.22	0.39

Table A4

Linear Mixed-Effects Model Estimates of Fixed Effects for Perceived Stress in the Blinded Wind Turbine Infrasound Exposure Experiment

Effect	Estimate	Standard Error
Intercept: Before first passive task	1.46	0.38
Symptomatic group	-0.37	0.56
After second passive task	-0.38	0.26
Symptomatic group : After second passive task	0.11	0.38

Table A5

Linear Mixed-Effects Model Estimates of Fixed Effects for Perceived Stress in the Sham Infrasound Exposure Experiment

Effect	Estimate	Standard Error
Intercept: After baseline passive task	0.85	0.60
Symptomatic group	2.24	0.88
After passive task with sham instruction	0.08	0.69
After passive task with truthful instruction	-0.16	0.78
Symptomatic group : After passive task with sham instruction	0.10	1.02
Symptomatic group : After passive task with truthful instruction	0.13	1.12

Table A6

Linear Mixed-Effects Model Estimates of Fixed Effects for Perceived Stress Across the Course of the Experiment Day

Effect	Estimate	Standard Error
Intercept	1.37	0.51
Symptomatic group	-0.24	0.76
Time	0.04	0.05
Symptomatic group : Time	0.30	0.08

Table A7

Linear Mixed-Effects Model Estimates of Fixed Effects for the Mean Amplitude of Skin Conductance Responses (microsiemens) in the Blinded Wind Turbine Infrasound Exposure Experiment

Effect	Estimate	Standard Error
Intercept: During passive task with wind turbine infrasound exposure	0.64	0.17
Symptomatic group	0.26	0.25
During passive task with no acoustic stimulus	0.05	0.11
Symptomatic group : During passive task with no acoustic stimulus	0.05	0.16

Table A8

Linear Mixed-Effects Model Estimates of Fixed Effects for the Number of Skin Conductance Responses in the Blinded Wind Turbine Infrasound Exposure Experiment

Effect	Estimate	Standard Error
Intercept: During passive task with wind turbine infrasound exposure	4.61	1.76
Symptomatic group	-0.26	2.58
During passive task with no acoustic stimulus	1.07	1.30
Symptomatic group : During passive task with no acoustic stimulus	1.32	1.94

Table A9

Linear Mixed-Effects Model Estimates of Fixed Effects for the Mean Amplitude of Skin Conductance Responses (microsiemens) in the Sham Infrasound Exposure Experiment

Effect	Estimate	Standard Error
Intercept: During baseline passive task	0.61	0.15
Symptomatic group	0.25	0.22
During passive task with sham instruction	0.21	0.20
During passive task with truthful instruction	0.15	0.22
Symptomatic group : During passive task with sham instruction	-0.44	0.29
Symptomatic group : During passive task with truthful instruction	-0.23	0.31

Table A10

Linear Mixed-Effects Model Estimates of Fixed Effects for the Number of Skin Conductance Responses in the Sham Infrasound Exposure Experiment

Effect	Estimate	Standard Error
Intercept: During baseline passive task	6.81	2.07
Symptomatic group	0.01	2.98
During passive task with sham instruction	-0.49	1.85
During passive task with truthful instruction	-0.52	2.12
Symptomatic group : During passive task with sham instruction	0.31	2.69
Symptomatic group : During passive task with truthful instruction	0.75	2.93